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EDDY PROCESSES IN THE GENERAL CIRCULATION OF THE JOVIAN ATMOSPHERES

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Two fundamentally different views of the general circulation of Jovian atmospheres have emerged. According to one view, espoused by G. Williams, the observed jet streams at the cloud tops are controlled by the vorticity transfers of small scale eddies generated by planetary wave instabilities within a shallow atmospheric layer. According to the alternate point of view argued by F. H. Busse, A. P. Ingersoll and their colleagues, the zonal jets are surface manifestations of deep interior convection organized into cylindrical motion with axes parallel to the planetary rotation axis. Both approaches may be considered in the context of the very different roles assumed by the potential vorticity. A possible reconciliation of the two kinds of dynamical systems is considered in which the interior motion is overlaid with a statically stable "capping layer" driven by turbulent energy injection from below. A simple model for the eddy driving of quasi-geostrophic dynamics in the capping layer is presented which is consistent with the tentative evidence for up-gradient momentum flux on Jupiter and IRIS observations of thermal contrast correlations with cyclonic and anticyclonic shear zones. Certain synoptic-scale cloud features in Jupiter's atmosphere are interpreted as breaking waves, which may also influence the lateral mixing of tracers such as the ortho-para hydrogen ratio.

Two basic ways of looking at the dynamics of the atmospheres of the giant planets have emerged in the last few years. One of these regards the visible surface features and wind systems as manifestations of "shallow layer" dynamics. According to this view these features can be understood in terms of energy generation, scale interactions, and dissipation within the layer, no more than a few scale heights deep, that is directly observable. The leading proponent of this point of view is Gareth Williams (1979). The alternative point of view is that the observable features are surface manifestations of the dynamics of the deep interior. Among the proponents of this view are Busse, and Ingersoll and Pollard (1982).

In both approaches, potential vorticity plays a central role, but it enters in fundamentally different ways. In the shallow layer view, the relevant component of vorticity is in the direction of the local vertical, and its variations arise largely from variations of the vertical component of planetary vorticity as fluid parcels move meridionally in the thin layer. These variations are responsible for the "β-effect", and the dynamics is analogous in many ways to those of Earth's atmosphere and oceans. In the deep dynamics view, the relevant component of vorticity is parallel to the planetary rotation axis and variations arise largely from stretching of axially aligned fluid columns as they move toward or away from the rotation axis. Such a dynamical regime would be fundamentally different from that of Earth's atmosphere and oceans.

There is some observational justification for each point of view. In support of the shallow layer dynamics point of view, Williams has shown that the multiple jet structure and certain features of the Jovian eddies are produced by an "earth-like" shallow layer dynamics model driven by solar forcing. On the other hand, such features as the longevity of the Great Red Spot (GRS) and large ovals, the high speed of Saturn's zonal jets, and the large negative values of the meridional gradient of absolute vorticity observed near Jupiter's easterly jets seem to require a strong influence of deep dynamics, though they do not necessarily indicate cylindrical structures parallel to the rotation axis.

Can these two points of view be reconciled? In this paper, some features of the deep dynamics scheme are first reviewed, and a scheme for surface layer dynamics is proposed in which the statically stable cloud level region acts as a "capping layer", driven by turbulent energy injection from the interior. In this layer, the amplitude of large scale deep circulation features decreases with altitude. The possible roles of breaking internal gravity waves and Rossby waves, and the influence of lateral mixing of tracers such as the ortho-para hydrogen ratio are also briefly discussed.

POTENTIAL VORTICITY IN THE DEEP INTERIOR

Figure 1 is a sketch of a possible structure for deep dynamics. The cylindrical sheets parallel to the rotation axis represent surfaces on which the zonal flow has a maximum. They are shown in the extreme idealization in which the zonal flow penetrates right through the planet, in which case there would be perfect symmetry beyween the upper and lower hemispheres. Superposed on this planetary scale flow are eddies consisting of tall thin axial cylinders. Such a regime might occur in the interior where potential density variations are sufficiently small that bouyancy forces are of the same order as vertical Coriolis forces and the dissipative time scale is not too short, i.e., probably not everywhere, but possibly in large regions of the interior.

Under these conditions, eddy motions could occur in planes perpendicular to the axis and would satisfy the circulation theorem in the form

$$\frac{dC}{dt} \simeq \frac{d}{dt}(\eta\delta A) \simeq 0 \tag{1}$$

where C is the absolute circulation around a small closed curve of area δA perpendicular to the rotation axis, and η is the sum of the planetary and relative vorticities. For long thin columns oriented parallel to the axial coordinate h, the continuity equation is

$$\frac{d}{dt}(M\delta A) = 0 \tag{2}$$

where M is the mass per unit area of the column, i.e.,

$$M = \int \rho dh,$$

where ρ is density, and integration is over the length of the column. Combining (1) and (2) gives

$$\frac{d\zeta}{dt} - v\ (2\Omega + \zeta) \cdot \left(\frac{d\ln M}{dr}\right) \simeq 0 \tag{3}$$

where r is the coordinate perpendicular to the axis, v is the associated fluid velocity, Ω is the planetary rotation rate, and ζ is the relative vorticity. This equation is analogous to the barotropic vorticity equation on a β-plane

$$\frac{d\hat{\zeta}}{dt} + \hat{v}\beta = 0 \tag{4}$$

where $\hat{\zeta}$ is the vertical (not axial) component of relative vorticity, $\hat{v}$ is the meridional velocity, and β is the meridional gradient of planetary vorticity, $\beta \equiv 2\ \Omega\ \cos\phi/a$ at latitude ϕ and planetary radius a.

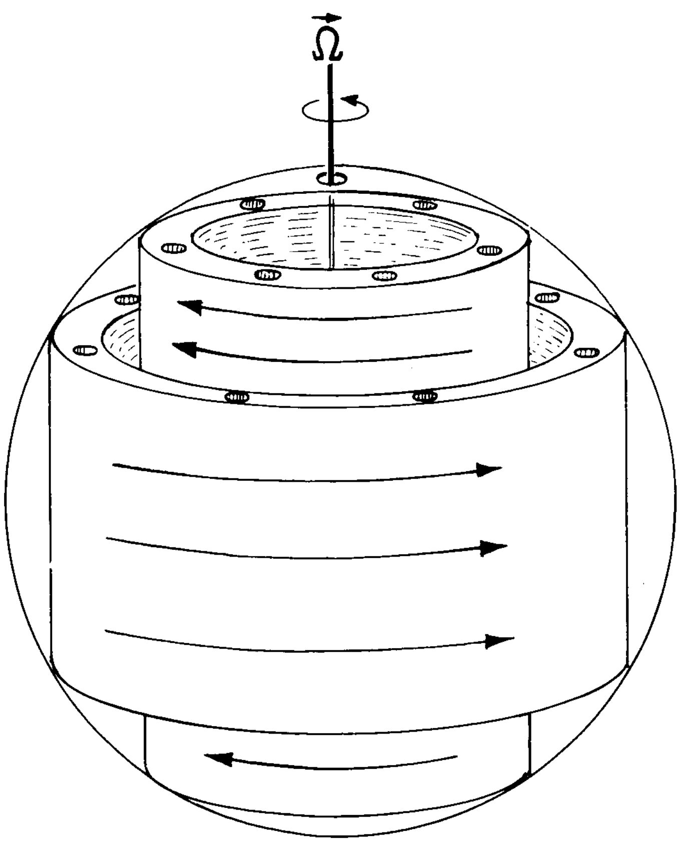

Figure 1. Possible cylindrical convection geometry in Jupiter's atmosphere.

Ingersoll and Pollard pointed out the possible applicability of equation (3) to the deep interiors of the atmospheres of the giant planets. They also called attention to two features of this equation: (a) It has small amplitude solutions analogous to Rossby waves, except that they propagate eastward rather than westward relative to the zonal wind $\bar{u}$ in which they are imbedded. Thus, observations of waves with slow eastward propagation speed might be diagnostic of deep dynamics. (b) For this deep dynamics model, there is a threshold of wave instability in regions where

$$\bar{u}_{rr} \approx 2\Omega \frac{d\ell nM}{dr} .$$

For isentropic columns whose length is constrained by the spherical shape of the planet, Ingersoll and Pollard have shown that this condition is approximately equivalent to

$$\bar{u}_{yy} \approx - 3\beta.$$

This condition can be contrasted with the more familiar threshold condition

$$\bar{u}_{yy} \approx \beta,$$

where y is the meridional coordinate, for a barotropic thin atmosphere. The large observed curvatures of the Jovian eastward jets might be indications of deep velocity structure.

The analogy between equations (3) and (4) encourages speculation about other possible aspects of deep dynamics. For example, should one expect an upscale cascade, analogous to that in barotropic flows, in which energy introduced at small scales is transferred upscale eventually appearing in zonally aligned jets like the cylindrical sheets sketched in Fig. 1? Does this system admit solutions corresponding to long-lived large scale features analogous to Rossby wave solitons or modons?

EDDY DRIVING OF THE SURFACE LAYER

We suppose that deep rooted zonal flow systems, perhaps like those represented by the cylindrical sheets in Fig. 1, exist in the interior, and ask how they might be modified by large scale zonal shear in the surface layer. In particular, we examine how such large scale zonal wind shear might be driven by convective eddies impinging on the surface layer from the interior.

In the surface layer, energy input is presumed to take place at a scale comparable to the Rossby radius of deformation,

$$L_R \sim NH/2\Omega\sin\phi ,$$

where N is the bouyancy frequency and H the scale height. Smaller scale convective eddies impinging on the surface layer would spread laterally until they reach the scale L_R. Based on the bouyancy frequency and scale height just below Jupiter's tropopause, $L_R \lesssim 2000$ km. This scale corresponds to a zonal wavenumber of 30 or more at middle latitudes. At scale L_R, the eddies should be horizontally isotropic, but energy would be transferred upscale in eddies of increasingly zonal orientation until the scale of the jets is reached. This energy decascade is expected to occur in the surface layer, and might occur in the deep interior. The jet scale L_j in the interior, if dominated by a potential vorticity conserving dynamics like that sketched in the last section would be

$$\hat{L}_j \sim \pi\ [\,|2\Omega(\frac{1}{M}\frac{dM}{dr})|/|\bar{u}|\,]^{-\frac{1}{2}} \quad .$$

In a barotropic surface layer, that scale would be

$$\hat{L}_j \sim \pi\ [\beta/|\bar{u}|\,]^{-\frac{1}{2}} \quad .$$

According to the model of Ingersoll and Pollard, the ratio $|2\Omega(\frac{1}{M}\frac{dM}{dr})|:\ \beta$ is about three, so matching of interior structure to a barotropic surface layer with the same jet structure would require a baroclinic boundary layer in which the magnitude of $\bar{u}$ decreases by about a factor of three.

Because the Rossby number and the scale ratio L_j/a are small, the surface layer circulation can be described by quasi-geostrophic dynamics on the β-plane. The important dynamical quantity is the quasi-geostrophic potential vorticity q which can be separated into eddy and zonal mean components, q' and $\bar{q}$:

$$q' = \psi'_{xx} + \psi'_{yy} + \frac{f^2}{p}\frac{\partial}{\partial z}\left(\frac{p}{N^2}\frac{\partial\psi'}{\partial z}\right) , \tag{5a}$$

$$\bar{q} = \int\{\beta - \bar{u}_{yy} - \frac{f^2}{p}\frac{\partial}{\partial z}\left(\frac{p}{N^2}\frac{\partial\bar{u}}{\partial z}\right)\}\ dy \ . \tag{5b}$$

The vertical coordinate is the log-pressure coordinate,

$$z = -\ H\ell n(p/p_s)$$

where p is pressure and p_s is a constant; ψ' is the geostrophic stream-function for the eddy component of the flow and f is the Coriolis parameter. The conservation of potential vorticity equation governs q',

$$\left(\frac{\partial}{\partial t} + \bar{u}\frac{\partial}{\partial x}\right) q' + v'\ \bar{q}_y = G' - J(\psi', q') , \tag{6}$$

where G' represents generation of q' by convective eddies at the scale L_R. Multiplication of q' and zonal averaging yields the equation for eddy enstrophy, $1/2\ \overline{q'^2}$:

$$\frac{\partial}{\partial t}\ 1/2\overline{q'^2} + \overline{v'q'}\ \bar{q}_y = \overline{q'G'} - \overline{q'J(\psi', q')} \quad . \tag{7}$$

Changes in the zonal flow are described approximately by

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v}_* = \overline{v'q'} \tag{8}$$

where $\bar{v}_*$ is the residual mean meridional velocity. The residual mean circulation satisfies the continuity equation

$$\frac{\partial \bar{v}_*}{\partial y} + p^{-1} \frac{\partial}{\partial z} (p\bar{w}_*) = 0 \tag{9}$$

where the vertical residual mean velocity $\bar{w}_*$ is closely related to the zonal mean radiative heating rate $\bar{Q}$,

$$\bar{w}_* \simeq g\bar{Q} / (c_p T_s N^2) \tag{10}$$

where g, c_p, and T_s are gravitational acceleration, constant pressure specific heat, and a mean reference temperature. The heating rate can be approximated by the radiative damping representation,

$$(\bar{Q}/c_p T_s) = -\alpha_r T_s^{-1} (\bar{T} - \bar{T}_e) \tag{11}$$

where $\bar{T}$ is the latitude dependent zonal mean temperature, $\bar{T}_e$ is the corresponding radiative equilibrium temperature, and $\alpha_r(z)$ is the radiative damping rate. The zonally averaged wind and temperature fields are in geostrophic balance:

$$\bar{u}_z = -(g/fT_s)\bar{T}_y \ . \tag{12}$$

Neglecting meridional variations of $\bar{T}_e$, equations (10)-(12) yield

$$\bar{w}_{*y} = \frac{f\alpha_r}{N^2} \bar{u}_z \ . \tag{13}$$

If the zonal wind shear distribution diminishes the amplitude of both easterly and westerly jets, equation (13) indicates that subsidence occurs in cyclonic shear zones and ascent occurs in anticyclonic shear zones (Fig. 2).

Using (9), (13), and the steady state versions of (7), and (8), integrating over a layer of finite thickness Δz gives

$$\Delta\left(\frac{\alpha_r p}{N^2} \bar{u}_z\right) = \Delta(p\ \bar{w}_{*y}) = -\int_{\Delta z} p\ \bar{v}_{*yy} dz = \int_{\Delta z} p\ \overline{(v'q')}_{yy} dz \ . \tag{14}$$

The behavior of the factor $\alpha_r p/N^2$ is sketched in Fig. 3. Above the cloud tops N^2 increases upward, and $\alpha_r p$ decreases upward, so $\alpha_r p/N^2$ decreases upward.

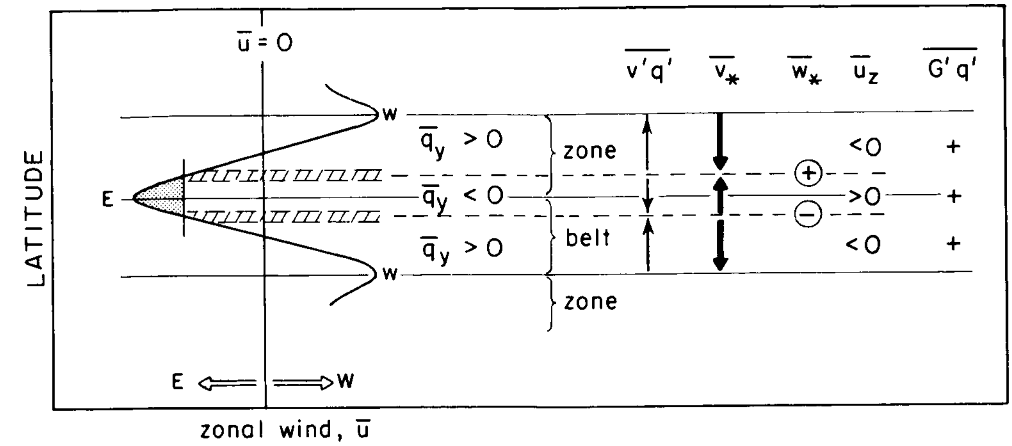

Figure 2. Possible dynamical relationships in a capping layer.

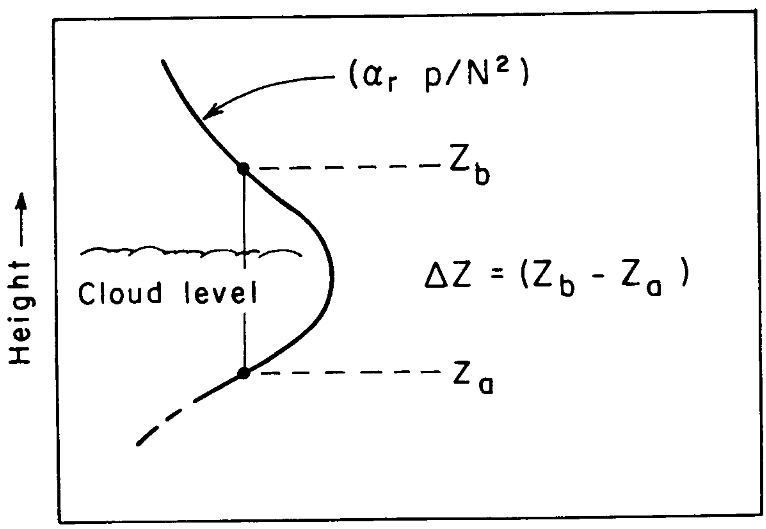

Figure 3. Schematic representation of $\alpha_r p/N^2$ as a function of height. Wind shear differences are taken across a layer such as (z_a, z_b) connecting levels where this factor has the same values.

Below the cloud tops $\alpha_r p$ decreases very rapidly downward, probably more rapidly than N^2, at least at intermediate depths. Under these conditions the layer can be taken to span the maximum of $\alpha_r p/N^2$ as indicated with end points at levels with equal values of $\alpha_r p/N^2$ in Fig. 3. Between these points the jump in wind shear is proportional to the pressure weighted integral of $\overline{v'q'}$,

$$\Delta\bar{u}_z \sim \left(\frac{N^2}{\alpha_r p}\right)_{za,zb} \frac{\partial^2}{\partial y^2} \int_{\Delta z} p\, \overline{v'q'}\, dz \,. \tag{15}$$

If the shear is relatively small at the base of the layer, and if the jet structure and associated eddy potential vorticity flux is oscillatory in y, the wind shear at the top of the layer is opposite in sign to $\int \rho \overline{v'q'}\, dz$. This is illustrated in Fig. 2.

According to (7), $\overline{v'q'}$ is closely related to potential enstrophy generation, either through stirring by upwelling turbulence (the term $\overline{G'q'}$), or through non-linearity (the term $-\overline{q'J(\psi',q')}$). The latter term is important where $\bar{q}_y$ vanishes on the shoulders of Jupiter's westward jets. It may also be important near the cores of the westward jets since the quasi-geostrophic instability condition, $\bar{q}_y < 0$, is likely to be satisfied there as a result of vertical as well as horizontal curvature of $\bar{u}$. In general

$$\overline{v'q'}\ \bar{q}_y \approx \overline{G'q'} - \overline{q'J(\psi',q')} \ , \tag{16}$$

and the right side will be positive where there is eddy stirring or baroclinic instability in westward jet cores, so that the sign of $\overline{v'q'}$ is the same as that of $\bar{q}_y$ in these regions. If eddy forcing occurs nearly everywhere, $\overline{v'q'} > 0$ in westerly jets, and $\overline{v'q'} < 0$ in easterly jets. Under these circumstances, according to (15) $\Delta \bar{u}_z > 0$ in easterly jets and $\Delta \bar{u}_z < 0$ in westerly jets. Thus, eddy forcing by upwelling convective eddies would generate shears in the capping layer as a result of the induced meridional circulation and associated Coriolis torques. These shears would reduce the magnitude of the internal jets through the cloud top region (Fig. 2).

This model is consistent with two observations: (a) If the flow is quasi-barotropic at the level of the observed cloud level winds,

$$\frac{\partial}{\partial y}\,(\overline{u'v'}) \simeq -\ \overline{v'q'} \tag{17}$$

there. The eddy momentum flux divergence would be negative in eastward jets and positive in westward jets. That is, it would act to intensify the jets. This relationship has been observed in some analyses of Voyager wind measurements, but this result is still somewhat controversial. (b) Zonal mean temperature at the cloud top level would be relatively low in anticyclonic shear zones and relatively high in cyclonic shear zones. This pattern is consistent with IRIS observations.

Clearly many details of this "capping layer" model have yet to be worked out, including the roles of thermal energy sources due to spatially varying solar and thermal radiation in the surface layer.

THE ROLE OF BREAKING WAVES

McIntyre and Palmer (1984) have recently argued that breaking planetary waves may play a very important role in the meridional transport of potential vorticity and passive tracers. Breaking occurs when initially adjacent fluid parcels rapidly separate and lose all correlation of their positions and velocities. For waves such as Rossby waves superimposed on a background zonal flow, an approximate criterion for breaking is $|u'| > |\bar{u}-c|$ where u' is the eddy zonal velocity and c is wave phase speed. An effect of wave breaking is to produce a region in which tracers are well mixed (the region of breaking waves or "surf zone", to use the evocative terminology of McIntyre and Palmer), adjacent to relatively narrow regions of strong tracer gradient. Figure 4 illustrates this structure for the tracer ozone in Earth's stratosphere. Note that a spiraling band of strong ozone gradient coincides with a spiraling wind maximum. The wind maximum is a manifestation of a maximum in the potential vorticity gradient in the same band. The band bounds an apparent region of planetary wave breaking.

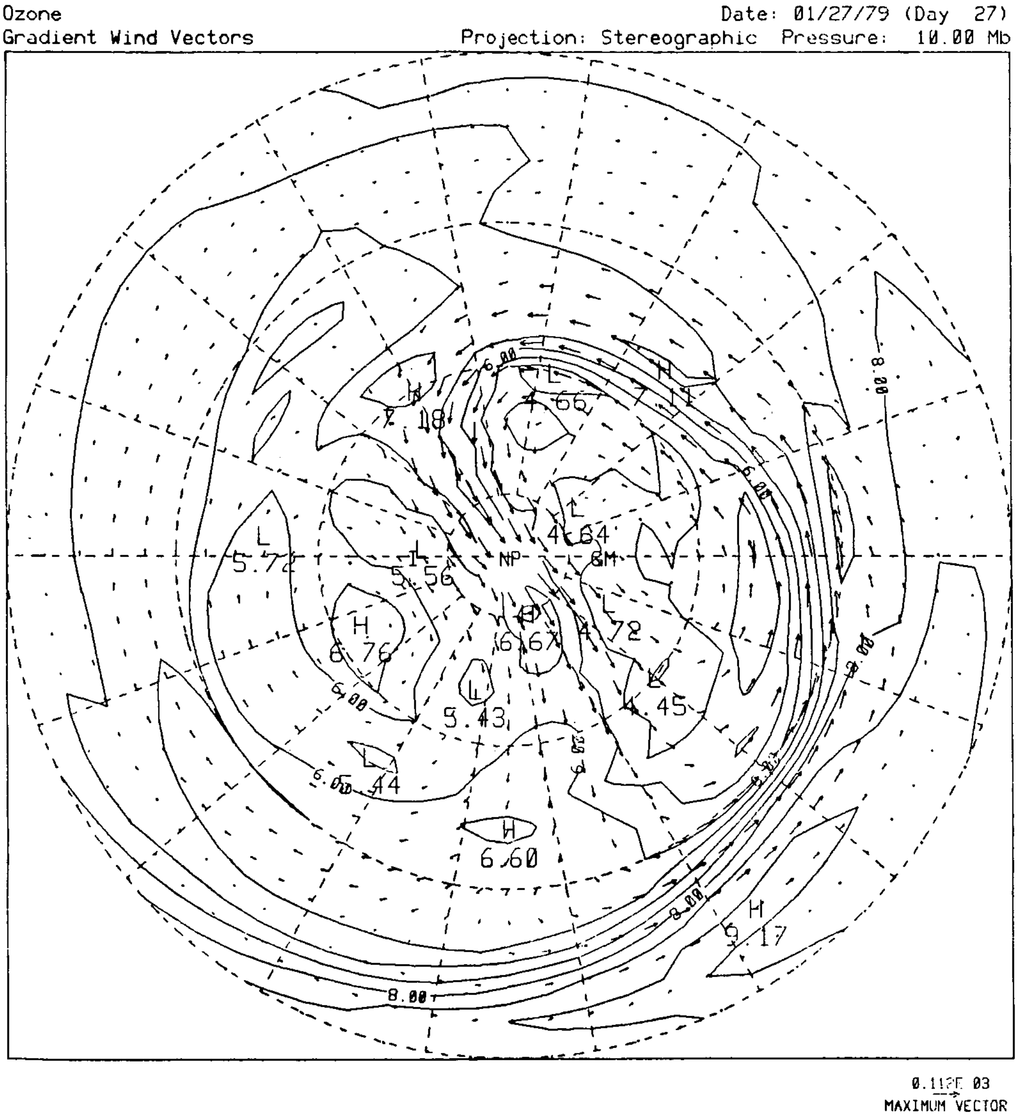

Figure 4. The "surf zone" structure at the 10mb level in the Earth's atmosphere. Ozone isopleths (ppmv) and gradient wind vectors (maximum speed 112 ms^{-1}). Note the correlation between ozone gradient and wind speed.

The cloud top region of Jupiter's atmosphere shares some characteristics with Earth's stratosphere. Potential vorticity is the important quasi-conservative dynamical variable, and there are observable "passive tracers", colored clouds in the case of Jupiter. Are there any features in the Jovian atmosphere which correspond to the wave-breaking/"surf zone" structure?

In the Cathedral of St. John the Divine nearby, several of us saw a stained glass window showing the planets, dating, I am told, from 1934. In rendering Jupiter, the artist has depicted the well-known zonally aligned belt and zone structure, and has chosen to show, in addition, a band stretching diagonally around the planet connecting two belts. A similar feature can be seen on Jupiter itself. Figure 5 shows a diagonal band extending from the equatorward edge of the GRS south westward to the polar edge. The region in which the band originates just west of the GRS is a region of particularly intense wave activity. It seems likely that this band is a manifestation of wave breaking on Jupiter analogous to the stratospheric structure shown in Fig. 4. What one sees in the Jupiter image is a sharp gradient of passive tracer, a cloud edge, with a spiral structure. Its tentative identification as the edge of a wave breaking zone would be confirmed if it was also found to be the locus of strong potential vorticity gradient, i.e., a wind maximum.

Breaking internal gravity waves are also important in Earth's atmosphere in that they exchange momentum between the surface and troposphere and the region above about 1 mb where these waves break. At the breaking level, they are very effective in shifting the zonal flow speed toward the wave phase speed. This is probably the reason zonal winds in the upper mesosphere are weak. Gravity wave breaking tends to reduce the flow speed to the phase speed of the waves, and for waves originating near the ground this phase speed is usually centered around zero. The same phenomenon must occur on Jupiter, so that zonal wind speeds in Jupiter's stratosphere, above about 1-0.01 mb, might reflect zonal wind speeds near the level of origin of the upward propagating waves, perhaps near the base of the stable layer where convection from the deep interior can generate gravity waves.

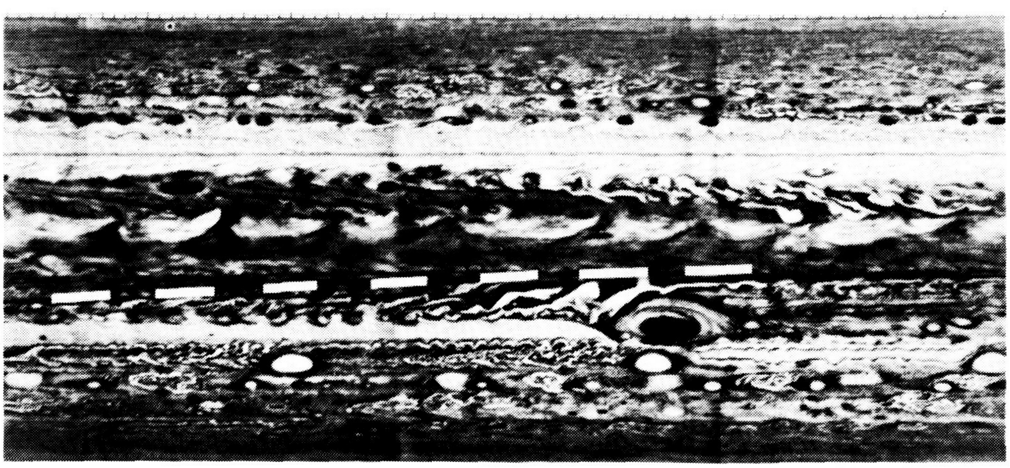

Figure 5. Possible evidence for spiral structure due to a "surf zone" in Jupiter's atmosphere in a cylindrical projection Voyager image showing about 220 deg of Jovian longitude.

There is an important exception to this tendency for upper-stratospheric zonal winds to resemble those at much lower levels. In the deep tropics, within 5-7 degrees of the equator, Kelvin waves would be generated, and these eastward propagating waves would be transmitted upward in preference to westward propagating Rossby-gravity waves that have short vertical wavelengths. Thus, Kelvin waves could produce systematic eastward acceleration in the equatorial stratosphere.

MIXING AND THE ORTHO-PARA H_2 DISTRIBUTION

It may be possible to understand the distribution of the ortho-para ratio given by Conrath and Gierasch (1984) in terms of a simple model of meridional mixing recently proposed by Holton (1986). At ~ 250 mb in Jupiter's atmosphere the time scale for ortho-para conversion is ~ 10^9 seconds. This is much longer than the radiative time scale at the same level. Consequently, the relatively steeply sloping isopleths of ortho-para ratio in the meridional plane closely approximate fluid parcel trajectories, while the relatively flat isentropes do not. The slope of the ortho-para ratio isopleths is determined by a balance between the tendency for the thermally driven residual mean circulation to tilt them and the tendency for meridional mixing to flatten them. Thus, the isopleth slope, $(dy/dz)_i$ is approximately

$$\left(\frac{dy}{dz}\right)_i \sim \frac{\overline{v'^2}}{w_* a \tau_e}$$

where $\overline{v'^2}$ is eddy meridional velocity variance and τ_e is characteristic eddy time scale. Thus, correlations between this isopleth slope and the belt-zone structure would occur only to the extent that $\overline{v'^2}/\tau_e$ correlates with the belt-zone structure.

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DR. BEEBE: Before I ask for questions I am going to excercise the chair's option and make some comments. With respect to your breaking waves--there are spiral patterns in both equatorial belts. As a matter of fact, the barges in the North Equatorial Belt are nested in spiral patterns. There are also spiral patterns in the North Temperate Belt, even when it is browner than it is in the Voyager data. On the front cover of the conference program notebook there is a feature which is schematically drawn along the south edge of the Equatorial Zone. This feature actually distorts the zonal wind flow and when it catches up and passes the Red Spot, it carries white cloud material from west of the Red Spot along with it. This forms a white cloud with a strong north-south wave pattern east of the Red Spot. The maxima of the wave translate at a constant velocity but the north-south extent of the pattern grows and becomes increasingly turbulent as it is sheared apart in the zonal flow. It is destroyed in about 40 hours. The location of the barges and the destruction of this wave pattern are located in the equatorial belts at latitudes where there is a bump in the latitudinal gradient of the zonal wind. Considering the fact that you have a discontinuity in the zonal wind shear where these phenomena occur, it may indicate that your surf zone is visible in the average zonal wind profile.

DR. LEOVY: Yes. Looking at the data from this point of view one may find a lot of things. It seems to me that there are two kinds of slanted patterns. One is that of a smaller scaled chevron which probably consists of individual systems and these have a relatively steep slope. On the other hand, the net effect of the mixing of potential vorticity or tracers produces, I suspect, a more gradual spiral.

DR. HUNTEN: Do you have a number for the angle specifying the slope of the stratospheric surface?

DR. LEOVY: That depends on the root-mean-square velocity and I haven't looked carefully at that. But the expected angle of such a spiral can be crudely estimated as follows. The rate of lateral spread of a breaking zone should be of order V/L, where V and L are characteristic eddy velocity and length scales. The zonal stretching rate should be of order $\bar{u}_y$. Hence, the angle of the spiral with respect to latitude circles is of order $V(L\bar{u}_y)^{-1}$. For the Jovian band, L appears to be comparable to the scale of zonal wind shear. Hence, the observed angle, ~ 1/20, might be attributable to eddies whose characteristic speed is ~ 1/20th of the scale for the zonal mean flow in the latitude belt.

DR. STONE: Conway, in your discussion of the shallow layer quasi-geostrophic dynamics you showed the definition of the potential vorticity gradient and related it to the stability criterion. You said that you thought that the vertical derivative term would really be negligible but you also estimated that the radius of deformation was 2000 km or less and the scale of the jets is the order of 20,000 km; so I would have thought that the opposite would be correct, that the vertical derivative term would be much more important than the horizontal derivative term.

DR. LEOVY: Well, I'm not sure. It's pretty hard to see how you can piece together a vertical and horizontal jet structure to make a stable configuration. In other words you have to make a funny looking jet, one which looks like an antijet in the vertical in order to stabilize the system.

DR. STONE: Ah, I wasn't saying it would be stable if you could calculate the vertical term. I'm just suggesting that the zeros might be very differently located.

DR. LEOVY: They might be quite differently located, and that's one of the problems we have. We can't ignore that term. But the observed cloud drift winds may nevertheless be at a level at which horizontal shears dominate.

DR. ALLISON: Conway, your quasi-geostrophic representation of the thin layer dynamics, as I understand it, is of a class with the order one Burger number regime for which the Rossby radius is roughly the same, in order of magnitude, as the observed length scale. But some of us think it's possible that Jupiter might have a thin layer system with a very weak stratification and such a small Burger number that a different type of quasi-geostrophic dynamics prevails. Gierasch and I have studied a thin layer system with a very nearly adiabatic lapse rate, for which the horizontal variation of the geostrophic winds is the same at all altitudes. The vertically integrated vorticity equation for such a system, assuming appropriately small vertical velocities at the bottom of the layer, leads to a shear stability criterion which will admit a zonal flow curvature as large as 3β. But the instability constraint for this system applies to the westward jets, unlike Andy Ingersoll's new 3β instability constraint on eastward jets for deep cylindrical flow. It's possible that Reta Beebe can help us distinguish between these two very different systems by assessing the relative frequency of instability features at westward as compared with eastward jets.

DR. LEOVY: Yes. I would only claim that the picture of a forced zonal wind "capping" layer that I have described is only one of several possible pictures and you have to look at several kinds. The underlying assumption of this view is that the eddies that are important are those at the Rossby radius of deformation scale. The others are irrelevant in determining the modification of the jet structure in the stable layer. That may or may not be true. So far, I don't believe it is ruled out.

DR. READ: Just to comment along the same lines or the same sort of topic: You mentioned the possibility of the Rossby radius being the order of 2000 km and it being significantly smaller than the Red spot and white oval spots. In our experiments with laboratory systems we can actually produce a flow in which N^2 varies very strongly with height. The definition of the Rossby radius then becomes very much more complicated. In particular I would certainly like to argue for the possibility that things like the Red Spot and the white ovals could in fact reflect the true scale of the Rossby radius. It depends on where you put the top boundary. A second point, which is related, is connected with looking at the $\bar{q}_y$ shape and where it goes to zero. In the particular laboratory system that I spend part of my time looking at, it is possible to observe a configuration where $\bar{q}_y$ actually goes through zero both in the vertical and in the horizontal and yet which still maintains the presence of a stable wave train.

DR. LEOVY: How is that wave train generated?

DR. READ: Well, it's generated initially primarily by baroclinic instability. The point is that the profile would suggest that both baroclinic and barotropic instability processes can operate. I think the crucial thing to be borne in mind also is that these criteria are necessary conditions, they're not sufficient conditions.

DR. LEOVY: Yes, that's right, they're necessary but usually sufficient for some combination of baroclinic/barotropic instability. However, I'd like to comment on the idea that the Rossby radius is large. The 2000 km Rossby radius is based on the static stability near the tropopause, not low down. Since static stability decreases downward I don't see how you could get an effective Rossby radius which is very much larger than that.

DR. READ: The crucial thing is what you take for H. It's been customary to just plug in the pressure scale height but I don't think there's any fundamental reason why that should be.

DR. LEOVY: It's customary to plug in the pressure scale height and the effective vertical scale may be smaller than that, but it can't be larger. In a compressible atmosphere, the largest vertical scale for an unforced disturbance is the scale height.

DR. FELS: Am I correct in understanding that you were saying that selected vertical propagation of Kelvin waves in the tropics may account for the eastward acceleration of the equatorial stratosphere?

DR. LEOVY: I think one could draw that implication from what I said, but that's really not what I think is the mechanism for the equatorial superrotation in the Jovian case.

DR. FELS: Why couldn't one equally well have the mixed gravity-Rossby waves propagating?

DR. LEOVY: Well I think you could but as you know it's going to have a generally smaller vertical scale and it's not going to be able to penetrate as deeply and for that reason the Kelvin wave tends to be more effective. The reason I think Kelvin waves are nevertheless unimportant for what we see in the Jovian clouds is because these clouds occur at relatively high densities. If we saw an equatorial acceleration up around 0.1 mb or so, then I'd be more inclined to attribute that to Kelvin waves.

DR. EMANUEL: In one sense it seems to me that this discussion of scales relative to the deformation radius is irrelevant in assessing the stability and I suppose I can explain it this way. The Ertel potential vorticity is conserved regardless of scale; it's a three dimensional vorticity. In fact the Charney-Stern theorem can be generalized to say that you essentially have to have a local extremum of that quantity on an isentropic surface. In a sense you could ask the question, in view of the fact that it's a conserved variable, how are you ever going to produce that situation? Of course on the

Earth that constraint is not generally satisfied and the reason baroclinic instability exists is because of the effect of the rigid lower boundary. Again an internal maximum of potential vorticity in a fluid seems to be problematic regardless of scale.

DR. LEOVY: We do have, I think, an example in the Earth's atmosphere where one does get an internal instability and that's in the easterly jets of the stratosphere. Aside from that I think you're right. The Rossby radius is probably only relevant, if at all, in a consideration of the relative importance of the vertical derivative term as compared with the horizontal term in the potential vorticity, as Peter Stone pointed out.

DR. EMANUEL: I really don't see what that has to do with practicality and necessity.

DR. ORTON: Would you comment briefly on relevance to putative anticorrelative meridional temperature structures between tropospheres and stratospheres?

DR. LEOVY: If I understand your question, the reason that I emphasize the gravity waves is that we have good reason to believe that gravity waves in the Earth's atmosphere drive the winds in the mesosphere where the waves break, reducing the wind speed to that region where the waves are formed. That's how the mesosphere knows that it should have a zero wind velocity at some level. So what one has to ask for on Jupiter is: how do the winds at an upper level know that they ought to have some velocity and what velocity should that be? They might want to have the velocity associated with the zonal flow speed at the level where the waves are generated.

DR. BEEBE: Thank you. Before we leave I would like to call your attention to the fact that there are poster papers associated with this session. Please consider the first one. I would really like input from you. This poster deals with IAU standards for atmospheric nomenclature and I think this is probably the biggest group of users that we would get together for this sort of situation, so the input you would have would be quite significant.